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## Review Article

# Structural health monitoring of asphalt pavements using smart sensor networks: A comprehensive review

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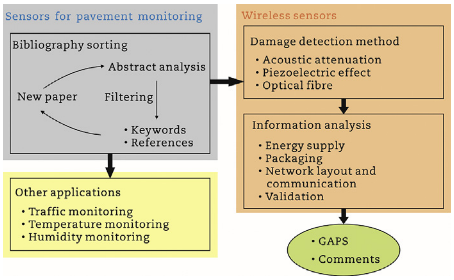
## HIGHLIGHTS

- An in-depth review on wireless sensor network for pavement health condition monitoring is provided.
- Article research and analysis method is presented.
- Sensors and networks features are deeply studied.
- Research gaps are presented and discussed.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Early, effective and continuous monitoring allows to reduce costs and to extend life of road infrastructure. For this reason, over the years, more and more efforts have been made to implement more advanced and effective monitoring systems at ever more contained costs, going from impractical manual and destructive methods through automated in vehicle equipment to the most recent wireless sensor network (WSN) embedded into the pavement. The purpose of this paper is to provide a comprehensive, up-to-date critical literature review of wireless sensor networks for pavement health monitoring, considering, also, the experience gained for wired sensor as fundamental point of reference. This work presents both the methodology used to collect and analyse the current bibliography and provides a description and comments fundamental characteristics of wireless sensor networks for pavement monitoring for damage detection purposes, among which energy supply, the detection method, the hardware and network architecture and the performance validation procedures. A brief analysis of other possible complementary applications of smart sensor networks, such as traffic and surface condition monitoring, is provided. Finally, a comment is provided on the gaps and possible directions that future research could follow to allow the extensive use of wireless sensor networks for pavement health condition monitoring.

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## 1. Introduction

The European road network consists of 5.5 million km mainly managed under local and regional responsibility. The annual maintenance spending in road infrastructures in the European Union (EU 25) accounts for about 30 billion euro (ERF, 2014). In the last decades, and more is expected in the future, approximately 90% of works involved the maintenance and upgrades of existing roads with only 10% of investments for construction of new roads. Despite this huge amount of expenditure, lack of information and political awareness on the importance of enough investments and appropriate works for the maintenance of the road infrastructure lead to its chronic underfinancing and deterioration. The lack of appropriate and timely maintenance, making the road network decay and loss of asset value, produces increase in the cost of future treatments and vehicle operating costs with negative impact on environment in terms of use of natural resources, greenhouse gases (GHGs) emission and energy consumption.

Therefore, in order to timely identify maintenance needs, early, effective and continuous monitoring is needed to reduce total costs and to extend pavement service life. For this reason, over the years, more and more efforts have been made to implement more advanced and effective monitoring systems at ever more contained costs, going from impractical manual and destructive methods through automated in vehicle equipment to the most recent wireless sensor network (WSN) embedded into the pavement.

A smart sensor network is an embedded WSN made by a set of sensors, called nodes, integrated into the structure of interest in pre-determined positions, to monitor a particular event (e.g., appearance and propagation of concealed cracks) or measure a parameter (temperature, pressure, etc.) continuously and in real time, communicating wirelessly with at least one Sink Node, with computation and/or storage functions (Akyildiz et al., 2002). Sink node are integrated with antennas for data transmission, allowing remote monitoring. Smart networks are designed to be self-powered and to optimize energy efficiency and sensing capabilities.

WNSs for the structural health monitoring system of civil infrastructure have already been widely described (Alavi et al., 2016b; Lynch, 2006; Noel et al., 2017; Yun and Min, 2011) but their application for pavement monitoring is a still new topic and literature lacks an in-depth survey that takes stock of the situation to understand the advantages and limitations of this new technology.

Therefore, the purpose of this paper is to provide a comprehensive, up-to-date critical literature review of the application and availability of wireless sensor for pavement health monitoring, considering, also, the experience gained for wired sensor as a fundamental point of reference.

This work aims to present and comment on the fundamental characteristics for understanding the WSN for pavement monitoring. The introduction is followed by a brief description of the review approach, which lists the phases of the research and cataloguing work, the most recurring keywords and the development of the topic over time. The third section provides a summary of the development of pavement monitoring techniques, from destructive external systems up to the WSN. The fourth section deals with the energy supply for these sensors as one of the main limits to their diffusion. Fifth and sixth sections allow to understand respectively the methodologies used to identify the damage of the pavement and the structure of the sensor and of the network in which it is inserted. The seventh section provides an overview of the validation of the performance of these systems through numerical simulations, experimental tests and full-scale applications. The eighth section, finally, aims to describe other uses of wireless sensors embedded into the pavement, other than the structural health monitoring purpose.

Conclusions focuses mainly on gaps and possible directions that future research could follow to allow the extensive use of wireless sensors for pavement health condition monitoring.

## 2. Review approach

The approach followed in the literature review is divided into the following phases: (a) identification of new papers on academic journals and databases; (b) analysis of keywords and bibliography; (c) filtering and cataloguing articles; (d) selection and organization of information. This process is briefly summarized in Fig. 1.

As for the first phase, since the topic has immediate practical implications, the research has extended not only to the most relevant journals, but also to reports and publications outside the research field.

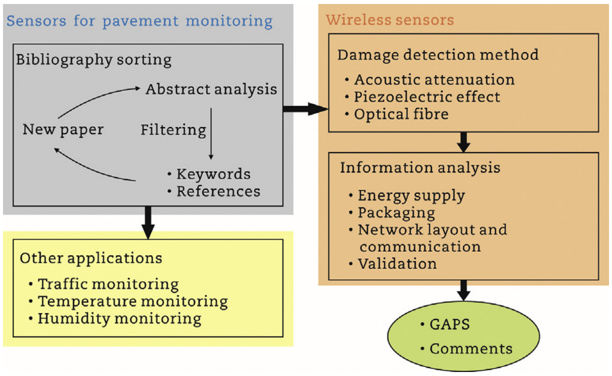

**Fig. 1 – Review approach scheme.**

The articles were identified firstly based on keyword research on the main publication search engines (Google Scholar, Scopus, etc.) and afterward by consulting the references of the articles accessed. In Table 1, in particular, the keywords of the most relevant articles on the WSN for pavement health monitoring are grouped by frequency of appearance, useful for the purpose of this research and for future investigations.

The set of articles thus identified was filtered and the documents were divided into those whose main topic concerns the wireless monitoring of road pavements from those dealing with other topics but still necessary to understand the progress of the technology and research applications.

Each article was read and analysed, and the relevant information was extrapolated and catalogued in a specific table. Among the relevant information, in addition to the general data such as year, authors, journal and keywords, also purpose, energy supply, operating principle, packaging, communication system, and so on were considered.

This analysis has allowed us to highlight how research on these new technologies has been growing for the last two decades, with over half of the publications falling between 2016 and 2019.

## 3. Background

The development of monitoring techniques has allowed, over the years, to investigate the conditions of the pavement without intrusive or destructive surveys, reducing the effects on the operating conditions of the road.

This non-destructive monitoring methods can be divided in external evaluation methods and in situ pavement sensors (Xue et al., 2014). External methods, manual or automated, allow to detect pavement distress through deflection, acoustic emission, ground-penetrating radar, ultrasound, infrared thermal imaging and laser technology. These monitoring approaches, even if are suitable for integration with GIS platforms for automatic data collection and analysis (Fakhri et al., 2019), they require significant manpower, time and the use of costly equipment and, in addition, are not able to detect micro-damage and its development (Ji et al., 2019a, b, c; Rhimi et al., 2012).

Moreover, excluding the instruments that measure deflections that have an impact on traffic and a not negligible cost (Cafiso and Di Graziano, 2009), many of these methods generally reflect the distress conditions of pavement surface rather than the internal stress/strain state and structural degradation of pavement (Dong et al., 2018).

In-situ pavement sensing technology is based on a wide selection of sensors (moisture, pressure, strain, temperature, etc.) able to collect pavement performance and environmental information continuously and in real-time, overcoming the aforementioned limitation of traditional external methods (Alavi et al., 2016a; Hasni et al., 2017b). These kinds of systems, widely adopted in civil infrastructures for structural health monitoring (SHM), guarantee an efficient and reliable transmission of data through a wired communication between sensor and repository. Many studies have been done on wired embedded sensing network and their full-scale application. Timm and Priest (2004) installed strain gauges, pressure cells, moisture and temperature sensors in different layers of pavement structures at the NCAT test track to investigate the dynamic responses under live truck loading. Mn/ROAD is an heavily instrumented pavement testing facility in Minnesota with the purpose to study mechanical pavement response for varying levels of vehicle axle load configuration, speed and tyre type and pressure (Lukanen, 2005). Another important testing facility is the Virginia smart road, with twelve instrumented road sections in Blacksburg for the pavement load response monitoring (Al-Qadi et al., 2004; Loulizi et al., 2006). The PEGASE instrumentation platform represent a further fundamental example of embedded sensors for pavement smart monitoring systems validate in real scale testing facility (Duong et al., 2019). The French Institute of Science and Technology for Transport, Development and Networks (IFSTTSR), within the project 5th generation road, launched a wireless modular platform (the aforementioned PEGASE) reusable, without any additional cost or long development. This instrumentation is defined modular as it is composed by a "mother board" and "daughter boards" (Sohm et al., 2012), the first integrates computation, communication and storage, the

**Table 1 – Most frequent keywords extracted from analysed articles.**

| Frequency | Keyword |
|---|---|
| 3 or more times | Lead zirconate titanate (PZT), self-powered wireless sensor, structural health monitoring (SHM), asphalt pavement, acoustic wave |
| 2 times | Concealed damage, damage detection, finite element modelling (FEM), intelligent monitoring, pavement health monitoring (P-HM), pavement management, piezoelectric effect, sensor, traffic monitoring |
| Once | Accelerometers, adaptive working, axle detection, computational intelligence, crack, damage, data fusion, energy detector, fatigue cracking, fatigue prediction, infrastructural health monitoring, internet-of-things, low power sensors, moving load, near field connection (NFC), non-constant injection rate, pavement deflection, pavement energy harvesting, pavement vibrations, pavement–vehicle interaction model, piezo-floating gate sensor, polyvinylidene fluoride (PVDF), real-time pavement monitoring, remaining fatigue life prediction, radio-frequency identification (RFID), sensor networks, smart self-powered sensors, vehicle classification, weigh-in-motion (WIM), wireless sensor |

others integrate application-specific needs, so as to improve energy yield of the system (Le Cam et al., 2011). Even though the platform can be interrogated wirelessly, communication between sensor and mother board is established through wires.

On one hand, wires provide a reliable communication link, but on the other their installation can be very expensive and labour-intensive (Lynch, 2006). For this reason wireless sensors networks (WSNs) are increasingly emerged since the beginning of the millennium (Bennett et al., 1999) as a powerful low-cost platform to extend lifespan of structures by enabling earlier damage detection without routine inspection costs (Noel et al., 2017).

The main obstacle for the widespread use of these systems could concern energy supply. Commercially available sensors require the use of battery or solar systems that doesn't allow continuous long-term application. Periodic replacement of batteries due of their lifespan (about 1–2 years (Lajnef et al., 2011), until four month for light batteries (Nataf and Festor, 2013)) remains cost-prohibitive and impractical as well as solar power technology, despite the studies on sizing and lifetime maximization (Fedele et al., 2018; Long et al., 2009). A viable solution could be energy harvesting, that is the process of converting ambient energy, such as vibration and strain, into electrical energy that can be used to power the sensor (Lajnef et al., 2013).

The following paragraphs present an in-depth analysis of the energy production methods and of the fundamental characteristics of the wireless sensor networks to better understand their working principle and development potential.

## 4. Energy supply

One of the most important limitation of the widespread use of wireless embedded sensor for pavement heath monitoring is the power source. As mentioned in previous paragraph, batteries and solar panel turn out to be not suitable for long-term applications. A solution can be found in harvesting ambient energy, in particular, mechanical energy transmitted by the vehicles to the road pavement. The moving vehicles cause stress, strain, deformation and vibration in pavement, or, in other words, mechanical energy that is dissipated as wasted thermal energy. Piezoelectric materials are able to harvest this energy and transform it into electric energy and vice versa. These types of materials are first polarized by adding a strong electric field that after is removed, leaving a large strength of polarization. In order to maintain the neutrality of the material, free charge is absorbed on the polarization surface. When the strength of polarization is changed by the deformation of the material, some of the free charges is released to keep the electric neutrality. These charges, if connected to an appropriate route, can generate a current (Zhao et al., 2014).

The piezoelectric materials can work in two ways: direct and inverse piezoelectric effect. Direct piezoelectric effect describes the ability of the material transform mechanical strain into electrical charge, working as a sensor. Inverse piezoelectric effect, contrariwise, describes the ability to transform an applied electric potential into mechanical strain energy, working as an actuator (Sodano et al., 2004).

Lead zirconate titanate (PZT) is the most popular commercialized piezoelectric ceramic material utilized to prepare self-powered sensors due to its strong piezoelectricity and high dielectric constant. Commonly used commercially-produced PZT are PZT-4, PZT-5X and PZT-5H (Ji et al., 2019b). In particular, the latter is better suited for applications embedded into the pavement because of its high piezoelectric constant, dielectric constant an electromechanical coupling coefficient. The PZTs, on the other hand, are more brittle and stiffer than the asphalt mixture, which makes their deformation uncoordinated. As a result, PZT embedded into the pavement is more likely to be damaged. For this reason, piezoelectric polymer materials, such as polyvinylidene fluoride (PVDF), are used for their high temperature resistance and flexibility (Ji et al., 2019b; Lajnef et al., 2011). PDVF is a polymer that acquires piezoelectric properties through a stretching process that directs the polymer chains in a specific direction. Its characteristics, in spite of the lower piezoelectric coefficient (approximately 1/10 of the PZTs), make it more attractive for application as a sensor (Sirohi and Chopra, 2000).

A single piezoelectric transducer can generate large voltage signal (>10 V) with a limited current driving capability (<1 μA), limiting the level of extractable power (Rhimi et al., 2012). Furthermore, when transducers are embedded in pavement are able to produce one order dimension less voltage (Cafiso et al., 2013; Zhao et al., 2014), or, moreover, numerical analysis showed that, by embedding at 2 cm of depth energy collected is 241 times less than the surface (Xiao et al., 2017).

Although the power available to power the sensor embedded in asphalt pavement in very low, about few microwatt (Alavi et al., 2016a; Lajnef et al., 2011), it is compatible with sensor power demand that, thanks to their small size and operating systems, require less than 1 μW of power (Rhimi et al., 2012). This is also possible thanks to the use of new technologies, such as MEMS (micro-electromechanical systems) which provide useful advantages in long-term, continuous, real-time structural health monitoring of pavements applications (Ceylan et al., 2013), and, furthermore, the MEMS operating modes in terms of frequency of operation are well suited to the high-frequency capability of piezoelectric materials (Attoh-Okine et al., 2003).

Despite the low energy demand for their operation, it is not possible or useful to keep the sensors always active. The solution is to operate the systems according to a standby-active modes and allow an accumulation of charge system to collect the energy needed for operation in a few seconds (Wang, 2010). The problem is understanding how, when and for how long the sensor needs to activate to efficiently collect data.

The power consumption and the accuracy of a wireless sensor are inversely proportional and both depend on sampling frequency and the power level at which sensor transmit (Ghosh et al., 2014). Decreasing these two parameters increases the lifespan of the sensor but compromises the reliability of the data. For this reason, the discontinuous operation of the sensor allows a better energy efficiency while maintaining a good data quality. Within the SHM, several methods of this type are described. In Ghosh et al. (2014), the network is made of two master node equipped with an accelerometer that, when vibration signal exceeds a specified threshold, wake-up child nodes, or a number of sentry node wakes-up on a preconfigured scheme and communicates with a gateway node only when measured data exceed a certain threshold (Jang et al., 2010). Or, moreover, all sensor nodes are activated only when a damage in detected, so that it can be properly localized (Guo et al., 2016). In this way, the system allows damage detection in any case and, only if necessary, to locate it.

Although these operating schemes are designed for battery-powered sensors, even the energy harvesting architecture, between two harvesting opportunities, is energy-limited and require similar energy-saving mechanism (Rault et al., 2014). Another typical aspect of the road pavement environment is that the voltage produced by the piezoelectric transducer can't be used directly by the sensor because it is characterized by inconstant voltage spikes and the energy of a single event is not enough to power the sensor. The solution is to accumulate this random energy due to the pressure of the vehicles and to foresee the opportune moment to release it. For this reason, Xiao et al. (2017) propose an adaptive data acquisition and delivery scheme based on the optimization of the turn-on and turn-off times according to the harvested energy and the characteristics of the supercapacitor with which the sensor is equipped. As regards vehicle detection, in the system proposed by Bajwa et al. (2011), the vibration sensor can operate in idle mode and raw data mode. In the first the sensor is in an energy saving mode and only the microcontroller and the transceiver turn on every 30 s to receive the synchronization packets. In raw data mode all systems are tuned on and the microcontroller wakes up every 1/512 s and samples the analog output from the accelerometer unit. The magnetic sensor, on the other hand, is always active but only transmits data when a vehicle is detected. A battery of 7200 mA·h can get a lifetime of 5 months in raw data mode up to 23 years in idle mode.

From the point of view of sensor lifetime, energy conservation algorithms, like the one described above, are of fundamental importance for battery-powered systems, allowing a monitoring time adequate for pavement monitoring purpose. Many other protocols have been proposed for WSNs to save energy and to prolong lifetime (Nakas et al., 2020).

It is not the same for self-powered systems for which these algorithms allow the most efficient use of the energy produced but marginally influence its lifespan. By their constitution, their survivability is no longer dependent on the availability of energy but on the degradation of the sensor itself. Their duration, therefore, cannot be assessed directly from their energy efficiency but through experimental tests and long-term full-scale applications of which, to date, the literature is still lacking.

## 5. Damage detection methods

The new monitoring technologies do not require the extraction of specimens from the pavement, so the damage is not measured directly but through the monitoring of pavement characteristics influenced by it (e.g., acoustic properties or elastic modulus). Knowledge of these quantities is of fundamental importance as it influences most of the characteristics of the sensor, such as packaging, energy supply system, materials, etc.

Ji et al. (2019b) propose a self-powered damage-detection piezoelectric aggregate that is based on the acoustic attenuation principle. The piezoelectric aggregates are embedded in different positions into the pavement, when one of them is excited by an external voltage it starts vibrating according to the inverse piezoelectric effect. The vibration energy is transmitted to the surrounding pavement particles and propagates as sound waves since to another piezoelectric sensor. Via the positive piezoelectric effect, the sensor transforms the vibration energy in a voltage-varying sinusoidal waveform, which can be detected by using a signal receiver. When the acoustic wave passes through the asphalt concrete (AC) is subjected to an attenuation that depends not only by the characteristics of the pavement materials and by the environmental conditions, but also by the presence and the severity of concealed cracks. The effect on acoustic attenuation due to material damage can be isolated from the other affecting factors that causes diffusion and scattering attenuation, such as asphalt concrete mix, propagation distance and environmental condition, by using the root main square deviation (RMSD) (Ji et al., 2019a) or the average absolute deviation (AAD) of the amplitude (Ji et al., 2019c).

Also Fedele et al. (2017a) investigate the propagation of sound wave through asphalt pavement to evaluate its health and validate this method through experimental investigation (Fedele and Praticò, 2019). They detect the vibroacoustic effect of vehicular traffic on the road pavement to associate an "acoustic signature" to a given level of deterioration. The method is based on the hypothesis that the spectral content of an acoustic signal that passed through an undamaged pavement is different from that of a signal that travelled through a damaged pavement. In particular, the power spectral density calculated from the finite Fourier transform and the position of the centroid of the periodogram can be used to identify the overall status of the monitored structure (Fedele et al., 2017b), associating every level of deterioration to a specific acoustic signature and, through the data collected, to forecast the changes in asphalt behaviour over the time (Fedele et al., 2021). Acoustic signature, associated with machine learning-based identification and classification method, is able to identify concealed cracks and to monitor their growth over time with a great accuracy (Praticò et al., 2020).

Another approach to investigate the level of damage is based on the study of the different reaction of the pavement when it is subjected to traffic load. Damage, in fact, would reduce the pavement's resistance to deformation and would be evident through a change in strain behaviour due to the worsening in the material moduli (Lajnef et al., 2011; Rhimi et al., 2012). Moreover, an important characteristic of piezoelectric is the correlation between applied strain and value of the produced voltage (Sirohi and Chopra, 2000).

Based on this characteristic, Lajnef et al. (2013) developed a self-powered sensor system for continuous structural health monitoring of asphalt pavements composed of a wireless integrated circuit sensor powered by a piezoelectric transducer. The sensor consists of a p-channel floating gate metal-oxide-semiconductor transistor which is connected to a constant current source that is powered by the piezoelectric transducer during traffic loads. The energy harvested by the piezoelectric transducer is used to inject electrons from the transistor channel onto different floating-gate cells that start recording input data at different supply potential. When the input signal exceeds different thresholds, the system starts measuring the duration of the events. So, the sensor records the cumulative time at specific voltage threshold which is proportional to voltage/strain droppage (Hasni et al., 2017b). In each sensor there are seven memory gates for data storage and an activation threshold level from which the sensor starts recording the cumulative droppage of the voltage/strain. Each gate is associated to a different strain amplitude. The output is a histogram distribution of relative frequencies of strain levels events. When damage appears in the pavement, a variation of strain distribution occurs, and its effect is evaluated on relative shifts of the probability density function (PDF) of the distribution (Lajnef et al., 2011).

Another way to monitor pavement condition is to take advantage of the information deriving from weight-in-motion (WIM) systems. WIM allows to monitor and weigh moving vehicles without the need to slow them down (Liu et al., 2007). To this end, modern technologies integrate magnetic sensors for vehicle detection and vibration sensors to weigh them (Bajwa et al., 2013). In particular, the vibration sensor is able to measure vertical accelerations that are closely related to deflections at a known pavement temperature and therefore to the structural response and the health of the pavement (Bajwa et al., 2011).

Finally, even if not yet integrated with a wireless communication technology, but potentially implementable in this sense, an important operating principle, validated in real scale (Chapeleau et al., 2017), concerns optical fibres. It is based on the use of fibre optic cable embedded in the pavement layer as distributed sensor. A common used solution are fibre Bragg grating (FBG) sensors, seen as promising candidates to replace conventional strain gauges for long-term applications in a harsh environment (Kara De Maeijer et al., 2019), are capable of monitoring any phenomenon that deform the fibre, such as variations in strain and temperature (Dong et al., 2018), measuring the drift of Bragg reflection centre wavelength (Tan et al., 2014).

## 6. Hardware design

WSNs have seen a strong development during the last two decades, increasingly precision and efficiency with reduced size and optimized shapes. We have seen an evolution from large systems constituting an instrumented core of the pavement (Bennett et al., 1999) up to technologies with dimensions comparable to those of concrete asphalt aggregates, so much so that it can be defined as self-powered damage-detection aggregate (SPA) (Ji et al., 2019b) or “smart dust” (Ferzli et al., 2006).

The purpose of this section is to explain how wireless sensor network are made, from packaging shapes and materials in relation to the operating principle, to network layout design, installation procedures, position within the pavement and operation optimization.

### 6.1. *Packaging*

A fundamental aspect of the sensors of a wireless network is to be able to survive and be integrate within the pavement. In fact, these devices are designed either to be installed on existing surfaces by drilling a more or less deep hole, or positioned during construction or rehabilitation operations through fast and minimally invasive operations (Bajwa et al., 2013). Therefore, the importance of the packaging is fundamental since the resistance and the external shape depend on it. Furthermore, the importance of optimizing the size of the packaging is clear if you think that, for example in the case of sensors that use MEMS technology, 75%–95% of the total cost of the sensor is linked to that (Attoh-Okine et al., 2003). The wireless sensors are designed to be embedded in the pavement, therefore, to operate in the most efficient way is essential that the sensor materials are compatible with asphalt material and construction processes. The sensors, in fact, are stiffer than asphalt, more fragile than aggregates and are more likely to be subject to damage. Furthermore, during the asphalt mixing and construction operations sensors are subjected to high temperature and pressure. Therefore, the sensors need a package made by materials resistant to high temperature and considerable loads which, at the same time, does not affect the sensing capabilities.

To ensure the compatibility of the sensor with the host material, in particular when it have to deform with the pavement, the stiffness of the package must be close, or better lower, than that of the pavement material (Rhimi et al., 2012).

In order to meet the required thermal and mechanical protection performance, internal circuits are often encapsulated into a packaging with an elastic modulus comparable with that of the pavement with an additional layer for thermal protection.

The mechanical protection of the strain gauges in the market is generally made of metal. This material, however, is not suitable for wireless sensors as metallic materials act as a Faraday cage and inhibit wireless communication (Lajnef et al., 2013). For this reason, different types of materials have been tested for this purpose, such as rubber, phosphor bronze and epoxy resin. Of these, epoxy resin has the higher energy harvesting efficiency and is the most suitable material to protect the circuits from high pressure and action of the aggregates (Xiao et al., 2017). Various materials have also been tested for thermal protection, including smooth-cast 385 and polyurethane foam, the latter of which has better characteristics.

Thanks to the protective layers, 90% survival of the specimens subjected to laboratory tests has been demonstrated (Lajnef et al., 2013).

On one hand, greater packaging dimension provides a better protection to electronic circuits, but, on the other hand, encapsulating a smaller diameter or height provides better sensing capabilities (Ji et al., 2019b). It is proved that up to 30% loss in strain can occur adding a mechanical protection to the transducer (Lajnef et al., 2013).

Another important factor that can affect the sensor performance is the shape that is closely related to the operation principle. As regards sensors based on strain variations, marketed wired gauges made for asphalt concrete applications are H-shaped for a better contact (Al-Qadi et al., 2004). Using a similar shape for prototypes allows to use the same installing procedures but it is likely that damage occurs at the anchors' corners due to stress concentration. A bone-shape package avoids stress concentrations and provides a better strain transmission (Hasni et al., 2017a).

Other shapes, such as cylindrical (Ji et al., 2019b) or spherical (Alavi et al., 2016a), are used based on the needs arising from the respective operating principle. Table 2 summarizes the types of sensors proposed by various authors, showing the type of energy supply, the operating principle, the packaging chosen.

Moreover, the type of distress to be monitored influences the packaging since on this depends the position of the sensor within the asphalt layers. In particular, for fatigue cracking transverse tensile strain should be measured at the top/bottom of the asphalt layer, instead, vertical compressive strain should be measured in the middle of the surface asphalt layer and of the base and on the top of subgrade for monitoring, respectively, of permanent deformation of surface, base and subgrade in order to collect information needed for different design methods (Dong et al., 2012).

### 6.2. *Network layout*

The challenge in designing the WSN lies in finding the minimum number of sensors that allows to maintain good data quality. An optimization problem therefore arises in which a limited number of elements must be associated with an infinite number of possible positions. Optimization can take place on the basis of certain parameters such as data quality, the maximum sensing coverage, the fault tolerance, the network connectivity and so on (Noel et al., 2017). In order to meet this need, the literature investigates the optimal wireless sensor placement (OWSP) through algorithms aimed to solve this complex optimization problem (Zhou et al., 2015) and to collect the most useful information and to reach the longest network lifetime (Zhou et al., 2017).

The structure of a WSN can be distinguished according to the elements present, their role in the network and the communication links that are established between them despite the damage detection method adopted.

Sensing capabilities are attributed to fundamental elements of the network called sensor nodes, which communicate via wireless short-range communication with a central node, which is capable of being interrogated by external equipment via radio frequency identification (RFID) technology. The radio signal, in fact, is able to cross the pavement and be readable to a few tens of centimetres without significant loss of information (Aono et al., 2016).

Based on the relationships between the elements of the network, it is possible to have centralized or even star-shaped schemes when all sensor nodes refer to a single central sensor/server or access point, or distributed, or mesh-type in which the various sensor nodes can communicate between them or, finally, a middle way, called two-tier network, in which the sensors are divided into clusters and, via short-range wireless communication, are connected with a reference central node, which, in turn, is connected via far-range high data rate communication to the central nodes of the other clusters (Lynch, 2006). Network architecture optimization, in fact, allows to reach the objective to collect and transmit data with the minimum energy consumption. In conventional scheme (CS) all the sensor nodes transmit to the AP directly, constrained with interference, limited distances, memory and processing capabilities. To overcome this constrains, it is not a viable solution to require every sensor node to transmit their data to the sink. For this reason energy-efficient data gathering algorithms have been presented to combine sensors information and to send only aggregate data (Dos Santos et al., 2014; Heinzelman et al., 2000; Meghanathan, 2013). Data gathering algorithms collects, aggregates and forward sensors data in several rounds trough communication typology based on the communication protocol type, for example "tree protocols" or "cluster protocols" (Liang et al., 2010; Meghanathan, 2015).

**Table 2 – Type of packaging compared to the energy supply system, operating principle and purpose of the sensor.**

| Source | Energy supply | Operating principle | Purpose | Packaging |
|---|---|---|---|---|
| Ji et al. (2019a, b, c) | Energy harvesting | Acoustic attenuation | Structural health | Cylindrical |
| Hasni et al. (2017a, b) | Energy harvesting | Constant/non-constant injection rates | Structural health | H-shaped |
| Xiao et al. (2017) | Energy harvesting | Not specified | Temperature, humidity | Not specified |
| Alavi et al. (2016a) | Energy harvesting | Constant/non-constant injection rates | Structural health | Spherical |
| Bajwa et al. (2013) | Battery | Magnetic, vibration | WIM | Box case |
| Lajnef et al. (2013) | Energy harvesting | Constant/non-constant injection rates | Structural health | H-shaped/bone-shaped |
| Rhimi et al. (2012) | Energy harvesting | Constant/non-constant injection rates | Structural health | H-shaped/bone-shaped |
| Lajnef et al. (2011) | Energy harvesting | Constant/non-constant injection rates | Structural health | Not specified |
| Bajwa et al. (2011) | Battery | Magnetic, vibration | Traffic and environmental condition | Box case |
| Cheung et al. (2005) | Battery | Magnetic | Traffic | Smart 'stud' |
| Knaian (2000) | Battery | Magnetic | Traffic and environmental condition | Box case |

Some examples of these node schemes have already been adopted for wired sensor networks and are an important starting point for the design of the WSN. Xue et al. (2015), for instance, propose a network designed for health and traffic monitoring made by "sensing groups". Each group is composed of different kind of commercial off-the-shelf sensors, such as horizontal strain sensor, vertical strain sensors, load cells, temperature and moisture sensor. As the sensors are very close to each other, the effect of vehicles wandering is negligible and the response of a sensing group is treated as at the same point in the transverse plane. All sensors are connected to a voltage-sensing data logger for wireless data transmission. Dong et al. (2018) describe a layout design scheme of sensing network of airport asphalt pavement for structural information monitoring in which the sensor matrix can be divided in three components, namely, response monitoring group, wandering determination group and temperature monitoring group. The first group consists of parallel rows of pressure cells and vertical, longitudinal and transverse strain sensors placed at different distances from the centreline in function of the configuration of the main landing gear of the most frequent planes, and a longitudinal spacing of 0.5 m between sensor of the same row. The wandering group has the purpose of determine the wandering of the aircrafts and, indirectly, its influence on dynamic response and distribution. It consists of seven transverse strain sensors embedded near the centreline, from 0 to 1.2 m with 0.2 m pitch, to detect the transverse position of each nose wheel. The last sensing group consists merely on two temperature sensors placed at 16 m from the centreline to eliminate aircraft loading effect. All the response data collected by the groups are transmitted wirelessly through a high-power wireless access point.

Some examples of networks made up of wireless sensors are presented in Cheung et al. (2005) and in Bajwa et al. (2011) where it is made up of a series of embedded wireless sensors identified as sensor nodes (SN) connected via radio to an access point (AP) located on the sides of the road, that processes the data received from SNs and transmits them via cable to a local station. While in this application the SNs are battery-powered, the AP can be line or solar powered. The embedded network consists of arrays of multiple vibration sensors located in the centre of the lane to minimize lane-to-lane interference and improve noise isolation (Bajwa et al., 2013). To solve the problem of traffic wandering, multiple sensors are installed and staggered both transversely and longitudinally. Since the most reliable data are those collected as close as possible to the vehicle wheel, the system will consider the sensor that records the highest vibrations (i.e., the nearest to the wheel).

Ye et al. (2018) propose a communication scheme of WSNs for pavement health monitoring in order to improve energy consumption performance when the network covers extended lengths. A strip clustering scheme (SCS) for data collection is presented to replace conventional scheme. In SCS the sensor network embedded in the road is divided into several strip-shaped regions with one cluster head node in each region and data are transmitted from non-head nodes to the head node one by one. After, each sensor aggregates all the data before transferring to the next one. The cluster head node, after data fusion, transmit the information to a higher-level cluster head node or to the AP. In this way, it is possible to obtain greater monitored areas with lower AP communication ranges, making easier further expansion of the network. This layout has better performance than the CS for monitoring sections over 75 m.

An important goal in the design of a wireless sensor network is to produce the maximum amount of information with the minimum number of sensors at an acceptable error level and to prevent breakage or malfunction. From this point of view, the closer the sensor is to the damaged area the better the detection is but installing too many sensors on the same section can be unsustainable and not useful.

Studies have been done on the optimization of sensor nodes optimal deployment in WSNs. For example, Khamlichi et al. (2017) propose an optimization method to obtain the minimum number of sensor nodes to achieve full coverage, based on the combination of a gradient method and the simulated annealing algorithm.

An effective strategy is to use the so called "group effect" (Alavi et al., 2016a), namely evaluating the missing information from nearby sensors. For this reason, Rhimi et al. (2012) use a probabilistic-based approach, called Kriging estimation technique, which estimate the attribute value at an unobserved position by interpolating the known values in the neighbourhood sensors. To achieve full reconstruction of the data in all the area with an average error less than 10%, the maximum horizontal spacing between placed sensors must be less than 20 cm (Lajnef et al., 2011). Alavi et al. (2016b) overcome this problem and of the loss of information due to the compressed data transmitted by the sensors using a hybrid damage detection method consisting on the application of a probabilistic neural network (PNN) and finite element (FE) analysis. Such algorithm is able both to analyse sensor data and to provide a precise diagnosis of the damage state.

## 7. Performance validation

The feasibility and the efficiency of a WSN system need to be tested to support future field applications. The validation methodologies of the wireless monitoring systems are described below, distinguishing the different experimental tests, the numerical modelling and the full-scale tests.

### 7.1. *Numerical and experimental validation*

In order to validate the efficiency of WSN for pavement structural monitoring purposes, numerical simulations and laboratory tests are carried out before full-scale experiments.

In general, numerical simulation is used as first step of sensor design process with the objective to obtain the necessary information for subsequent experiments. Furthermore, in this way it is possible to simulate the conditions that occur in full-scale applications, not obtainable in laboratory tests due to the limited size of specimens.

The goal of many studies is to understand, through 3D finite element modelling, the distribution of stress and strain in the road pavement layers due to the passage of a dynamic load (Alavi et al., 2016a) or in the specimen in AC subjected to bending-test (Hasni et al., 2017b) in order to understand the best position for the sensors, optimize their distribution and test the proposed damage detection algorithms (Rhimi et al., 2012). Another goal of the simulations is the validation of the energy production performances of the piezoelectric transducers due to the deformations in the road pavement induced by the traffic loads (Xiao et al., 2017).

For the purpose of applications on real roads, the data obtained from the numerical simulations are useful but not exhaustive. Therefore, it is necessary to test the properties of wireless sensors in a laboratory on small scale specimens.

Laboratory tests, in general, are aimed at validating self-powering characteristics, survivability, wireless communication capacity and above all damage detection.

The ability of the transducers to produce the energy needed to power the sensor is tested by inserting the transducer in a specimen subjected to direct tensile test (Cafiso et al., 2013), indirect tensile test or four-point bending beam (Lajnef et al., 2013) and studying the response in terms of voltage produced in relation to the applied load and survivability also according to the different types of packaging.

To test the efficiency of the sensors for cracks detection and their progression, a three-point bending beam test is used with a cut in the centre of the specimen to accelerate and control the fracture (Ji et al., 2019b; Rhimi et al., 2012). The sensors, immersed in the AC beam, are connected, via cable or wirelessly, to external equipment capable of measuring the response according to the operating principle used.

In Ji et al. (2019a), the high precision of the acoustic attenuation method is proven. By comparing both the measured and the monitored width, they find, for width from 0.67 to 4.31 mm, a maximum error of 4.2%. In Alavi et al. (2016a), the efficiency of the injection rate method is validated and the ability to monitor the damage progression is proven. Seven voltage levels, from 0.20 to 2 V with a difference of 0.3 V between each, are defined. They prove that the sensor is capable to detect damage progression in four damage configurations defined by four different crack lengths (0, 22.20, 31.75 and 44.45 mm).

Table 3 summarizes, for each article, the numerical simulations carried out, the experimental tests and the respective aims and quantities monitored.

**Table 3 – Numerical and experimental validation tests.**

| Source | Numerical validation | Result of numerical validation | Experimental validation | Result of experimental validation |
|---|---|---|---|---|
| Ji et al. (2019a, b, c) | Not specified | Not specified | Three-point bending test | Output acoustic signal (amplitude, frequency) at different notch width |
| Hasni et al. (2017a) | 3D FE pavement model under dynamic load | Asphalt response (strain/stress) | Not specified | Not specified |
| Hasni et al. (2017b) | 3D FE asphalt specimen under 3-point bending test | Asphalt response (strain/stress) at different locations and for intact or damage status | Three-point bending test | Sensor voltage at different notch width |
| Xiao et al. (2017) | 2D model of PZT transducer | Voltage output at different depth | Automatic rutting board | Energy efficiency for different packaging |
| Alavi et al. (2016a) | 3D FE pavement model under dynamic load | Asphalt response (strain/stress) at different locations and for intact or damaged status | Three-point bending test | Sensor voltage at different notch width |
| Lajnef et al. (2013) | • 3D FE model of the sensor under load<br>• Pavement model under dynamic load (viscoroute) | • Thickness of the package<br>• Asphalt response (stress/strain) | • AC between RF reader and receiver<br>• Four-point bending test<br>• Indirect tensile test | • RF propagation and loss of information<br>• PZT voltage output |
| Rhimi et al. (2012) | • Pavement model under dynamic load (viscoroute)<br>• Simple finite element for thermal protection evaluations<br>• 3D pavement model under traffic load | • Asphalt response (stress/strain)<br>• Conductivity/thickness of thermal protection layer<br>• Cumulative strain | • Environmental chamber (thermal protection evaluation)<br>• Slab compactor | • Isolation at different thermal protection thickness<br>• Survivability at different mechanical protection layer thickness |
| Lajnef et al. (2011) | Not specified | Not specified | • Four-point bending test<br>• Three-point bending test under varying temperature and load | Voltage output |

### 7.2. *In-field application*

In the last decade, despite their importance for a correct implementation of the system, the full-scale applications of WSN technology for structural pavement heath monitoring are very limited. In particular, most of the experiences are aimed at validating traffic monitoring systems instead of systems for structural health monitoring.

One of the few examples is presented by Lajnef et al. (2013) where the goal of the full-scale application is to evaluate the compatibility between the stiffness of the packaging and the hot mix asphalt (HMA) and to investigate the effect of different packaging configurations on sensors survivability.

Regarding WIM technology Bajwa et al. (2013) make a set of trucks of known weight pass through the sensor embedded into the pavement to validate the efficiency of the system and of the implemented model. The test highlights the difficulty in having reference data to be compared with those collected in the field to assess its reliability. The collection of data on different days allowed the evaluation of the effects of various environmental conditions.

These experiences are characterized by a duration of at most a few days and limited traffic flows. The literature lacks examples of long-term applications necessary to evaluate WSN performance and their feasibility within a pavement monitoring system.

## 8. Traffic and environmental condition monitoring

In addition to pavement damage monitoring, numerous sensors have been integrated into the pavements over the past two decades to obtain other types of information. With the ever-growing interest in intelligent transport systems (ITS), information regarding traffic flows and road surface conditions is fundamental for integrated and intelligent transport management.

### 8.1. *Traffic monitoring*

WSNs are widely used in the development of weight-in-motion systems for weighing and monitoring traffic at low cost and with good precision (Bajwa et al., 2013). In Bajwa et al. (2011), a WIM system capable of detecting vehicles through a magnetic sensor and weighing them through a vibration sensor is described. Thanks to axle detection (ADET) algorithm are able to classify vehicles basing on length, number of axles and axles spacing.

Cheung (2007) describes a magnetic and an acoustic sensor that, thanks to an adaptive threshold detection algorithm (ATDA), can achieve above 97% vehicle detection rate in field application and 90% on estimation of vehicles' speed and length.

In Huang et al. (2018), an IOT based volume and vehicle classification monitoring system is validated by laboratory tests, numerical simulations and field test. An algorithm is proposed to clean the data from signal noises, with a minimal error of 2.85% for axle spacing estimations and 4.6% for speed calculation.

### 8.2. *Pavement temperature and humidity monitoring*

Another important use of wireless sensors concerns the monitoring of environmental conditions. It is important to monitor temperature and humidity for two main reasons: to improve the accuracy of the sensors in detecting the structural health parameters of the pavement and to monitor the conditions of the road surface.

The temperature, in fact, has a strong influence on the asphalt properties and its knowledge is fundamental for any model related to the pavement stress/strain analysis. Bajwa et al. (2013) integrate the vibration sensor with a temperature sensor to collect the information necessary to implement an efficient vehicle–pavement interaction model. Lajnef et al. (2013) propose and test a temperature probe which can be used when necessary, e.g., during periodical non-destructive test (FWD, rolling wheel deflectometer, etc.).

Finally, through wireless monitoring of temperature and humidity it is possible to predict hazard conditions in the road surface or critical water content in unbound materials. Ong et al. (2008) design, built and validate a wireless, passive embedded sensor based on an inductor-capacitor resonant circuit for real-time monitoring of water content in civil engineering materials including asphalt pavement. Or, moreover, Pei et al. (2007) describe "smart dust" system for pavement moisture content and temperature monitoring in order to detect hazardous road conditions (dry, wet and icy) through special algorithms (Ferzli et al., 2006).

## 9. Conclusions, gaps and future research

Timely and efficient maintenance allows to reduce and prevent the costs associated with the deterioration of the road pavement. For this reason, over the years more and more accurate and less expensive techniques have been used, going from large destructive devices to monitoring systems integrated into the pavement.

Research in the field of pavement health condition monitoring is leading to the use of self-powered wireless sensors embedded into the pavement, capable of autonomously and at low cost monitoring the characteristics of the pavement and of transmitting information without the use of physical connections. For this reason, this paper presented a comprehensive review of literature and practice with a critical analysis of publication about wireless sensor networks for asphalt pavement with the aim of understanding the progress on this topic and to provide the foundation for future research and application.

The references collected through academic and non-academic search engines have made it possible to highlight some of the peculiar characteristics of the WSN, in particular shown as follows.

- Getting energy from batteries limits the life of the sensor. This problem can be overcome by piezoelectric transducers capable of harvest mechanical energy derived from traffic loads into electrical energy to power the sensor.

- Main damage detection methods were investigated such as monitoring the distribution of strains or sound waves and how these are affected by the presence of fractures.
- The shape of the sensor is closely linked to the damage detecting method and the resistance characteristics to be achieved. In particular, the systems that measure strain distribution are H-shaped or bone-shaped as they allow the coupled deformation of the sensor and the pavement. As far as sound waves are concerned, the packaging must only provide protection to the internal circuits for which spherical or cylindrical shapes of a size comparable to mix aggregates are preferred.
- Possible network schemes were investigated, highlighting their advantages and disadvantages, the position within the pavement according to the distress to be monitored and the algorithms able to locate and predict the damage progression based on the data collected from a limited number of sensors.
- Validation of sensor performance is done through numerical simulation, laboratory tests and full-scale tests. Numerical simulations and laboratory tests allow you to calibrate the parameters necessary for the following full-scale tests.
- Wireless sensors can also be used for applications other than SHM. Extensive development has taken place in the field of vehicle monitoring (counting, weighing, speed) and environmental parameters (temperature and humidity).

Study of literature allowed to draw conclusions on the state of the art in the research and on the gaps that still need to be filled. The main topics that future works could better investigate are briefly reported.

- Currently a large part of the research effort is focused on designing the sensor but still little has been investigated upon network layout that can optimize energy efficiency and that allows to obtain the best sensing capability.
- The lack of long term real scale application do not allow the evaluation of the impact that the presence of the sensors inside the pavement has both on the performance of the pavement itself and at the life cycle assessment, as well as the evaluation of the sensor survivability for long-term applications.
- Information on influence of environmental condition on sensors lifespan are also lacking.
- The WSNs for road pavement use the information collected with the aim of monitoring the width and propagation of cracks through indirect measurements (acoustic wave propagation, strain alteration, etc.). Further studies should be done on the possibility of using the data collected by the sensors to estimate stress and elastic modulus and, through these, to obtain an assessment of the decay of the pavement performance through time.
- Almost all attention is paid to internal crack monitoring, any wireless sensor is able to detect other types of distress, i.e., permanent deformations, pothole, patching, surface defects, which also affect pavement performance and safety.
- There is lack of considerations regarding lifecycle costs and performance in terms of economic performance compared to the commonly used monitoring techniques.

## Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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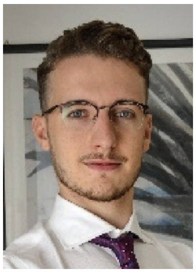

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**Salvatore Cafiso** is a full professor of highway geometric design and pavement engineering at the Department of Civil Engineering and Architecture (DICAR) of University of Catania. Prof. Cafiso was the past coordinator of the PhD course in engineering of transportation infrastructures, and director of the Infrastructures Transport laboratory (ITlab) at the University of Catania. He is the member of several scientific international committees, including TRB AHB65 "Operational Effects of Geometrics", TRB ANB10 "Transportation Safety Management", TRB steering committee of "International Symposium on Highway Geometric Design", PIARC Technical Committee "Design and Management of Safer Roads". Also, he is the author of more than 200 papers in international journals and conference proceedings.